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Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Method to Evaluate Potential for Ice Impacts on Sediment Stability

Uncertainty surrounding ice and sediment interaction introduces a high-level risk in the design of contaminated sediment remediation measures in rivers. Because much of the historic industrial activity in the United States is concentrated along northern rivers, many contaminated sediment sites are ice-affected. Furthermore, a high level of design uncertainty and risk results from the fact that no adequate analytical or numerical models exist to predict sediment transport under ice covers.

This technical note presents a practical method to assess ice jam occurrence and evaluate potential for ice-related impacts on sediment stability. The approach combines a review of historical ice jam information and analyses of geomorphic and hydrometeorological data with field observations. The primary objectives of the method are to determine if and where ice events occur, and whether or not these events affect sediment stability at locations of interest. This type of evaluation can be accomplished quickly and at a reasonable cost.

If it is found that ice-related transport of contaminated sediment has occurred, or is a real possibility, further investigation would be required. This could consist of bathymetric surveying and sediment sampling in suspected ice jam scour areas. Analysis of river-bed stratigraphy can provide more information on where and when ice-hydraulic scour and deposition occurred. Detailed numerical modeling of ice events can be used to calculate average under-ice water velocities and provide approximate estimates of shear stresses on the sediments.

Background

Sediment transport processes in ice-covered rivers can significantly differ from those occurring in open-water conditions. To date, engineering research on ice jams has focused mainly on causes and solutions to ice jam flooding. Only since 1990 have environmental issues associated with river ice received much attention (e.g., Prowse 1993). A limited understanding of ice–sediment interaction, combined with a lack of adequate analytical and numerical models to predict sediment movement under ice, introduces unknown and uncharacterized risk in the design of contaminated sediment remediation measures. The importance of river ice in the fate of contaminated sediments has gained attention through several high-profile cases, such as Montana's 1996 Milltown Dam (Fig. 1) ice jam flood, which resulted in the scour and subsequent transport of fluvial tailings (Moore and Landrigan 1999).

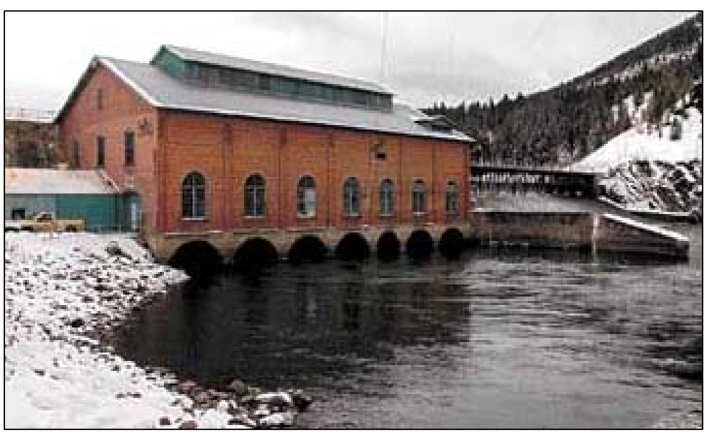

Figure 1. Milltown Dam.

The presence of ice has a range of possible influences on the sediment regime. Recent experiments at ERDC-CRREL show that, for the same depth and average water velocity, the addition of a floating ice cover dramatically changes the form of the vertical velocity profile, increasing turbulent shear stress on the bed as much as three times (Hains and Zabilansky 2004) (Fig. 2). This can cause the peak annual sediment-transport event for northern rivers to occur during the dynamic breakup of an ice cover or the release of a breakup ice jam, as has been observed by Walker (1969) and Milburn and Prowse (1996). These events often involve high discharges with gouging and abrasion of the bed and banks by moving ice (Prowse 2001, Prowse and Culp 2003). Ice in a river channel can reduce the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2005**	2. REPORT TYPE	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Ice Engineering. Method to Evaluate Potential for Ice Impacts on Sediment Stability**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Engineer Research and Development Center,Cold Regions Research & Engineering Laboratory,72 Lyme Rd,Hanover,NH,03755-1290**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

flow area, increasing under-ice water velocity, scouring bed sediments, and possibly shifting the path of the deepest flow. Ice accumulations also may impinge flow against the channel sides to erode the banks (Fig. 3) (Ettema and Daly 2004). Neill (1976) and Mercer and Cooper (1977) describe dynamic ice jam events causing local scour and re-suspension of sediment. Newbury (1968) and Smith and Pearce (2002) also report substantial scour at frequent jam sites.

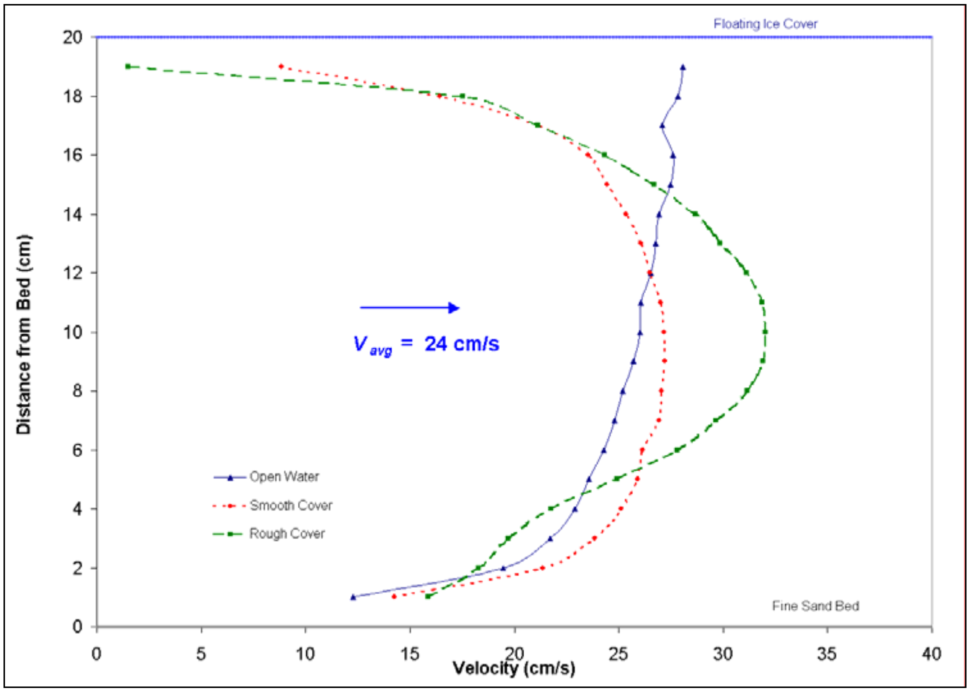

Figure 2. Vertical velocity profiles: Open water compared to smooth and rough ice cover cases. (From Hains and Zabilansky 2004.)

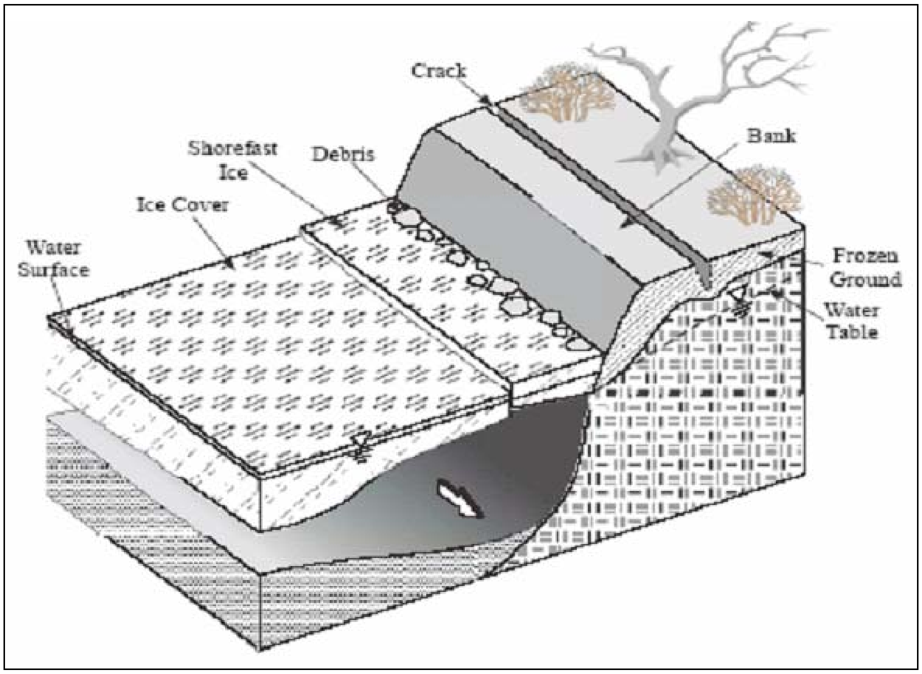

Figure 3. Ice cover impinging flow against the channel sides to erode and destabilize banks. (From Ettema and Daly 2004.)

Methods for evaluating potential impacts of ice on sediment stability are limited because no adequate analytical or numerical models for scour under ice exist at this time. This knowledge gap significantly increases the risk of failure in contaminated sediment remediation designs. The fact that many sites in the United States are located on ice-affected rivers and lakes emphasizes the importance of better understanding scour-under-ice issues and the need for reliable models. As a first step in addressing this problem, this technical note presents a practical method to assess ice impacts on sediment stability for the purpose of determining whether more detailed ice analyses are required.

Approach

The initial evaluation of ice effects on sediment processes combines background research on historic ice events with a field inspection for signs of past ice damage to river banks, structures, or riparian vegetation. Available meteorological and stream flow data are analyzed and correlated with the historic and observed evidence of past ice events. Major components of the initial evaluation are a review of historical information, analyses of hydrometeorological and geomorphic data, and a field inspection. These are described in more detail below.

Review of historic ice information

Background research on the ice regime typically begins with a review of historic ice information. The first source to check is ERDC-CRREL's ice jam database (IJDB) (http://www.crrel.usace.army.mil/ierd/ijdb/), which contains data on more than 14,300 ice events. Since this is a living database, omission of a particular site does not necessarily mean that ice events have not occurred. Local newspapers, libraries, museums, and historical societies also provide valuable information on past ice events. Concurrent review of hydrometeorological records can focus historical research by identifying periods that require more detailed review (e.g., Tuthill et al. 2003). Reports from past flood insurance studies may be useful for general hydrologic and hydraulic background material. Until recently, however, these studies usually did not consider ice impacts, assuming—often incorrectly—that stages associated with large open water floods overwhelmed any ice-affected high stages.

Locals familiar with the river are another valuable information source, particularly those who deal directly with ice problems, e.g., public works employees, local road agents, and emergency responders. In addition to historical ice jam information, the history of human activities along the river is important, including the location of dams and industry that may have affected the water or ice regime, or that may be sources of contaminated sediment.

Ice event "perception stage," the elevation below which an ice jam occurrence would not appear on the record (Gerard and Karpuk 1979), is often a limitation to the historical review and data collection effort. For example, an ice event that does not cause overbank flooding or other damage may be reported in an urban area where residents perceive a potential flood threat, but in less-populated areas, these types of events often go unreported. Similarly, an ice event that transports contaminated bed material but is below perception stage or occurs in a remote reach of river will likely go unnoticed. By this process, significant amounts of contaminated sediment could be transported to unexpected locations, potentially posing an unknown and uncharacterized risk to habitat and human health.

Review of geomorphology and ice processes

The lack of available ice records and uncertainties associated with perception stage require both a review of geomorphological processes related to ice and field observations to better characterize ice processes. Aerial photos and USGS maps are an excellent resource for examining geomorphic river features related to ice and sediment processes. Probable ice jamming locations, such as transitions from steeper to milder water surface slope, islands, channel constrictions, and bends, can be identified from maps and air photos. Longitudinal river profiles taken from flood insurance studies or constructed from USGS maps can provide important evidence on ice cover formation and transport processes.

Ice transport and deposition is similar to sediment transport processes, except that the buoyancy of the ice leads to deposition on the surface of the water rather than the river bed, as is the case for sediment (Shen and Wang 1995). Probably the most common locations for both sediment deposition and ice jam formation are transitions from steep to mild water surface slope at the upstream ends of pools or reservoirs. For the same reasons, river-to-lake confluences are common sediment deposition and ice jam locations. Other transition zones where average channel velocity and sediment-carrying capacity decrease are marked by mid-channel islands and sand bars.

Ice jams have caused hydraulic scour of contaminated bed sediments and their transport downstream, as occurred on the Grasse River in 2003 (Alcoa 2004). At the same time, upstream flooding from the jam may cause deposition of clean

sediment on top of the pre-existing contaminated bed material. Moore and Landrigan (1999) documented both of these phenomena on the Clark Fork River in Montana following a 1996 breakup ice jam. In this event, jamming on the Clark Fork River caused erosion and scour that transported a significant volume of metal-contaminated sediment from the Milltown Dam impoundment. Later, jamming on the Blackfoot River scoured clean sediments, which deposited in the Milltown Dam impoundment.

Most ice-related scour has been attributed to breakup ice jams, but freezeup ice jams often occur in the same locations as breakup jams and can cause bed scour at much lower discharges than breakup jam events. In the freezeup jam process, frazil ice formed in open water sections in the early winter slows down and accumulates at slope reduction points, constrictions, bends, islands, or bars, eventually arching across the channel. Additional floes will either accumulate against the upstream edge of the ice blockage, causing the ice cover to progress upstream, or be drawn beneath to thicken the ice accumulation. Once frozen in place, these thickened frazil ice accumulations (also known as “hanging dams”) can block the breakup ice run, resulting in upstream flooding and related ice jam scour. During the freezeup period, frazil accumulation and ice thickening in alluvial rivers with multiple channels can progressively block the main channel, forcing water flow into a parallel channel. Even at midwinter base flow levels, significant scour and re-deposition have been observed as a result of ice-induced channel shifting (Zabilansky et al. 2002).

Detailed information on ice-related deposition and scour can be developed through analysis of river bed stratigraphy (e.g., Alcoa 2004). These cases illustrate how better understanding of ice–sediment interaction would allow engineers to predict in advance how ice jam formation could enhance or degrade an emplaced cover, and design accordingly.

River profiles can be very useful in assessing jam locations since change in slope from steep to mild is highly correlated with ice jamming during ice cover formation and breakup. For example, Figure 4 compares the uniformly steep profile of the Cazenovia Creek upstream of Buffalo, New York, to the stepped pool-riffle profile of the Grasse River in northern New York. Based on the river profile, the ice on Cazenovia Creek would be expected to break up and run en masse, forming a single large jam near the mouth. The profile for Grasse River suggests a downstream-progressing sequence of breakups, jams, and releases. Field evidence verifies these assertions.

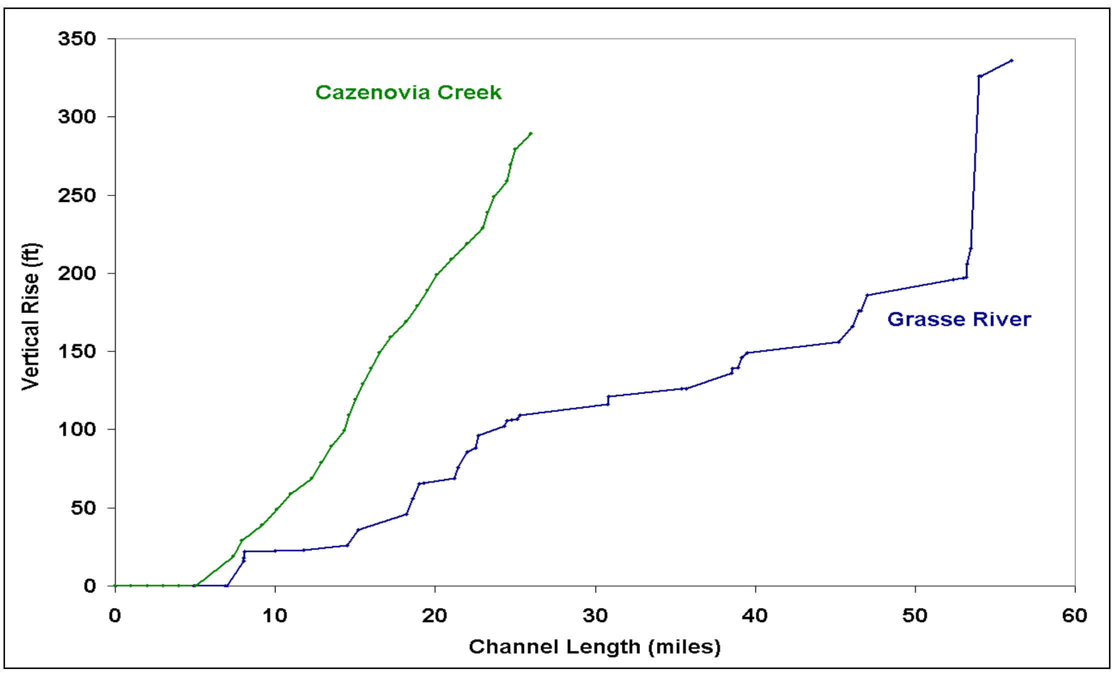

Figure 4. Comparison of Cazenovia Creek and Grasse River bed profiles.

The locations of structures, particularly dams and bridges, and their current condition are equally important in the identification of deposition and scour areas as these structures may retain or delay release of the ice cover during breakup. Analysis of maps and river profiles can also provide information on upstream ice and sediment source areas.

The implications of naturally occurring ice-related scour and deposition on the success of in-channel contaminated sediment remediation projects are clear. If jams are known to occur in the vicinity of the project, the remediation design must consider ice impacts to avoid contaminant dispersal. Conversely, ice-related sediment deposition could be used to reduce open-water scouring of remediation projects.

Review of hydrometeorological data

On northeastern rivers, fairly steady low flow is typical of the early-to-midwinter freezeup period. Midwinter thaws will cause spikes in the hydrograph that may or may not result in breakup, depending on various factors, including ice thickness, ice strength, and initial ice cover freezeup level. With the onset of spring thaw, stage and discharge rise in advance of ice breakup. At one extreme, the period between the start of rise and ice release may be as short as one day, usually resulting in dynamic and destructive ice events. Breakups of this type almost always involve significant rainfall, which accelerates snowmelt and causes rapid runoff into streams and rivers. At the other extreme, a gradual warming trend may prolong the hydrograph rise period up to several weeks, resulting in an extremely mild, thermally driven breakup.

Important components of a hydrometeorological data review include daily average air temperature, precipitation, and snowpack data, as well as river stage and discharge data. Ice thickness can be estimated from records of daily average air temperature and accumulated freezing degree-days (AFDD) (White 2004). Stage and discharge hydrographs, combined with AFDD-estimated ice thickness, can be used to identify likely dynamic ice breakup events associated with ice jams (Tuthill et al. 1996, 2003). ERDC-CRREL has assembled historic daily air temperature data for all National Weather Service first-order weather stations in the United States and calculated the annual series of AFDD from these data.[1] If available, historic stage and discharge hydrographs are extremely useful indicators of the nature and timing of ice breakup. It should be noted that the accuracy of discharge data is questionable when the rating curve is ice-affected.

Field inspection of study reach

A low-water field inspection of the river supplements the analyses described above. Field observations test initial assumptions on ice jamming locations, ice source reaches, and channel features and structures, and may offer the best clues to ice effects on sediment stability. If time and resources allow, a program of field observations during the winter season can be extremely useful in understanding freezeup and breakup processes.

Considerable research has addressed the effect of open water floods on vegetation and streambank stability (e.g., Fischenich and Allen 2000). Though less commonly exploited, the type of bank vegetation or its absence can reveal the nature and severity of ice action (Ettema and Daly 2004). Gouged or abraded river bank material may also provide evidence of severe ice runs in the recent past. Upstream of a known ice jam location, eroded gaps in the bank may show where flow escaped the main channel into the floodplain. Similarly, sections of riverbank may have scoured where overbank flow returned to the main channel downstream of the ice jam location. Figure 5 shows overbank flooding and sediment deposition from a 2003 ice jam on the Androscoggin River in Maine.

Ice scars on trees along riverbanks often provide the best evidence of past dynamic ice runs and ice jams. Maximum tree scar elevations usually result from ice jams, either as they form or release. A single tree can experience multiple ice scarring events with intervening periods of bark healing. By inspecting the scarred surface of the tree and counting annual growth rings, one can determine the years that the ice events occurred, and, to some extent, estimate the events' relative severity. Figure 6 shows an ice-scarred tree and a sawn section therefrom along the Grasse River. Graphical analyses of tree scars further illustrate historical ice jam elevations and longitudinal extent, as seen in Figure 7.

Conclusions

Ice and sediment interaction processes are not well understood and are not commonly considered in riverine remediation or channel stabilization projects. Thus, the risk of ice-scour-induced failure of in-channel contaminated sediment remediation projects and subsequent release of contaminated sediments is real, but often neglected. Evaluation of the potential for ice impacts on sediment stability is critical for northern rivers that experience ice effects, particularly since industrialization has taken place for up to several hundred years in some cases. This technical note presents a method to evaluate whether ice impacts on sediment stability should be considered in the design of a riverine contaminated sediment remediation project. If

[1] These data will be available on line in the near future. Contact Steven.F.Daly@erdc.usace.army.mil.

ice impacts are found to be significant, detailed numerical modeling of ice jams and estimates of their frequency and severity may be required.

Figure 5. 2003 ice jam on the Androscoggin River in Maine causing overbank flooding and sediment deposition.

Figure 6. Ice-scarred tree and sawn section from ice-scarred tree, Grasse River.

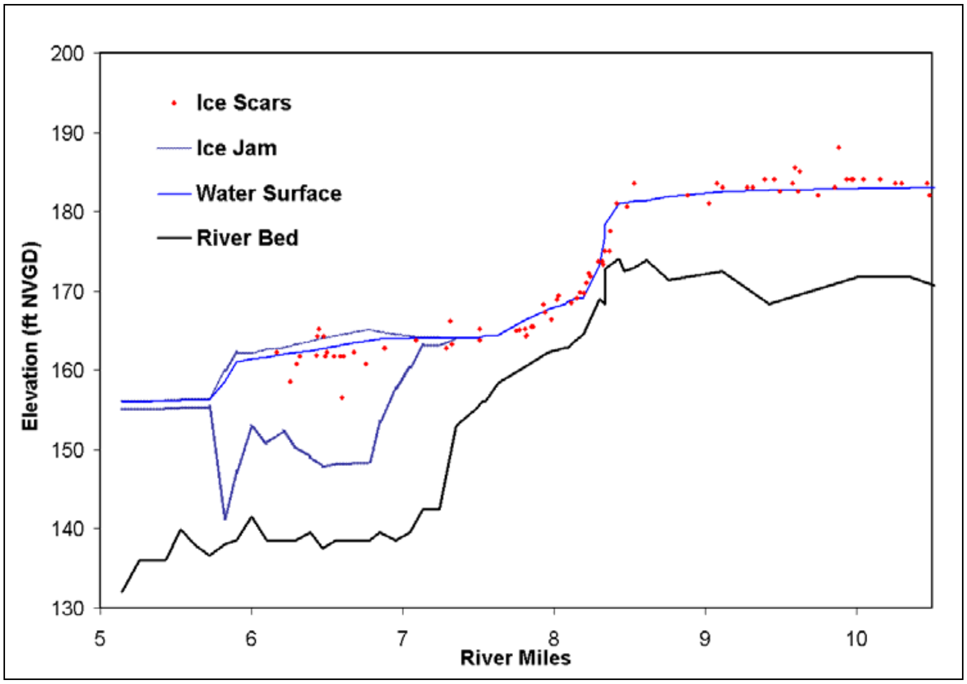

Figure 7. Ice jam profile and tree scar heights on the Grasse River.

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Acknowledgments

This work was supported in part by funding from the Civil Works Research-and-Development-funded Cold Regions Engineering work unit "Characterizing River Ice Impacts on Operation and Maintenance," CWIS # 39862.

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This issue of Ice Engineering was written by Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Group, Remote Sensing/Geographic Information Systems (RS/GIS) Water Resources Branch, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL); and Kathleen D. White, PhD, PE, Research Hydraulic Engineer, Environmental Sciences Branch, ERDC-CRREL.

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